Radio Synchrotron Emission From Weak Spherical Shocks

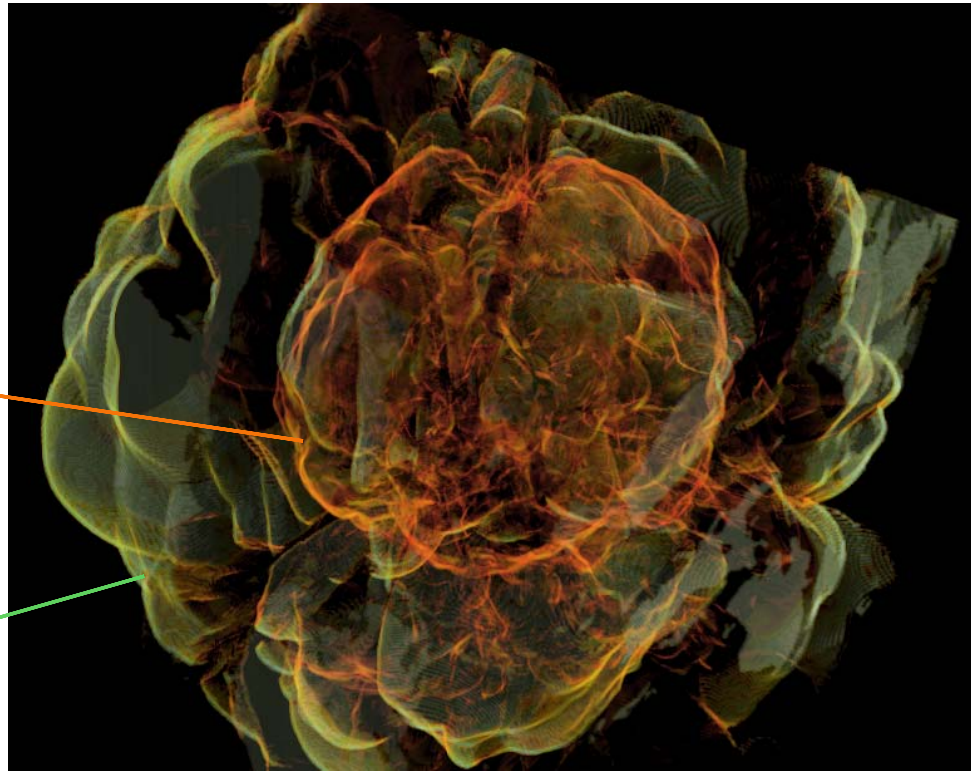
Hyesung Kang

Pusan National University, Korea

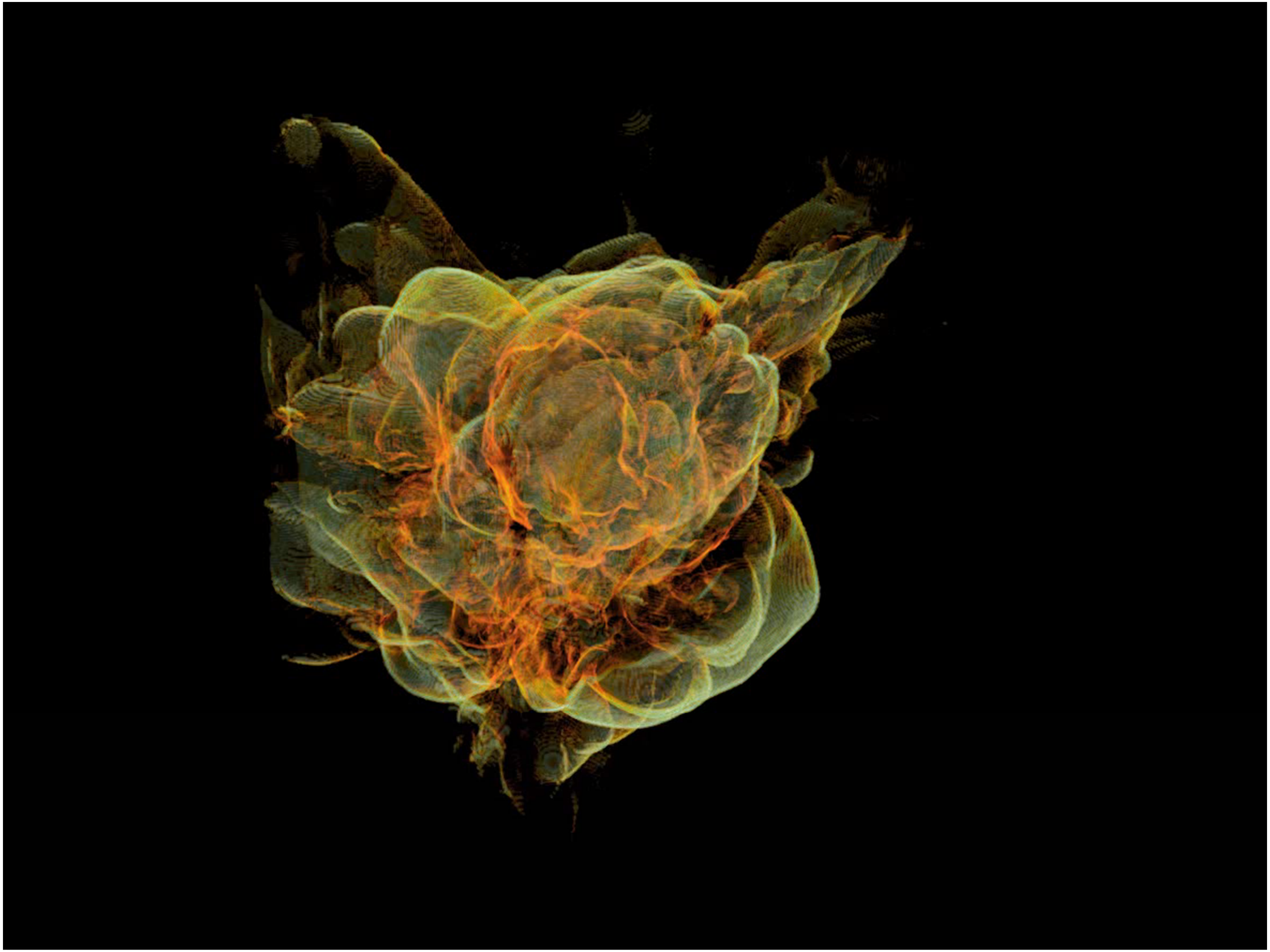
Vazza, Jones et al 2014 (in prep).

Weak shocks with M<4 (orange)

Accretion shocks with M>10 (green)



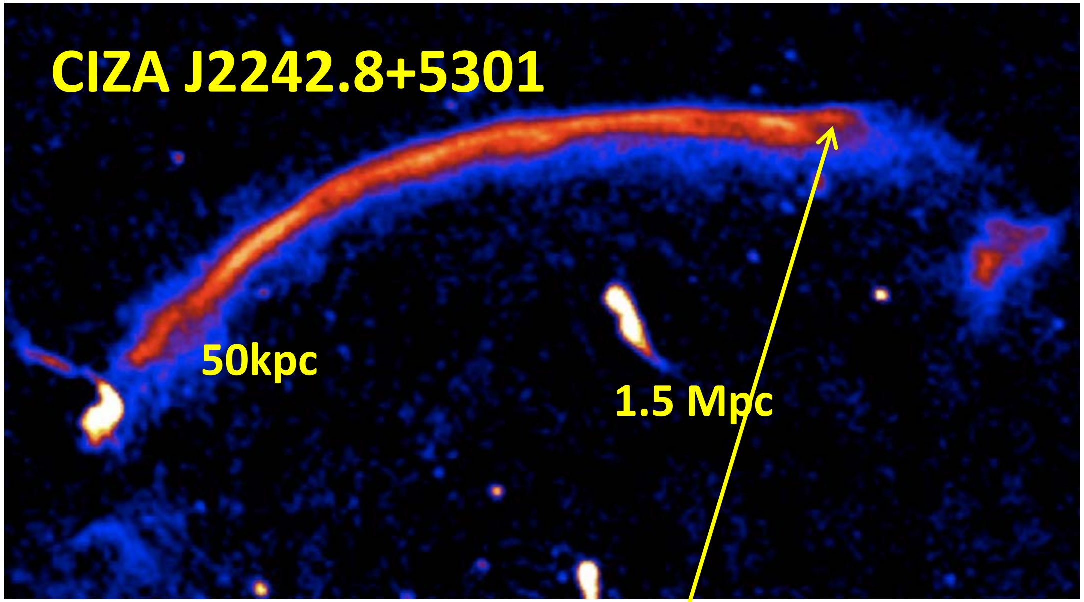
https://www.youtube.com/watch?v=yV3KPz0cPqk

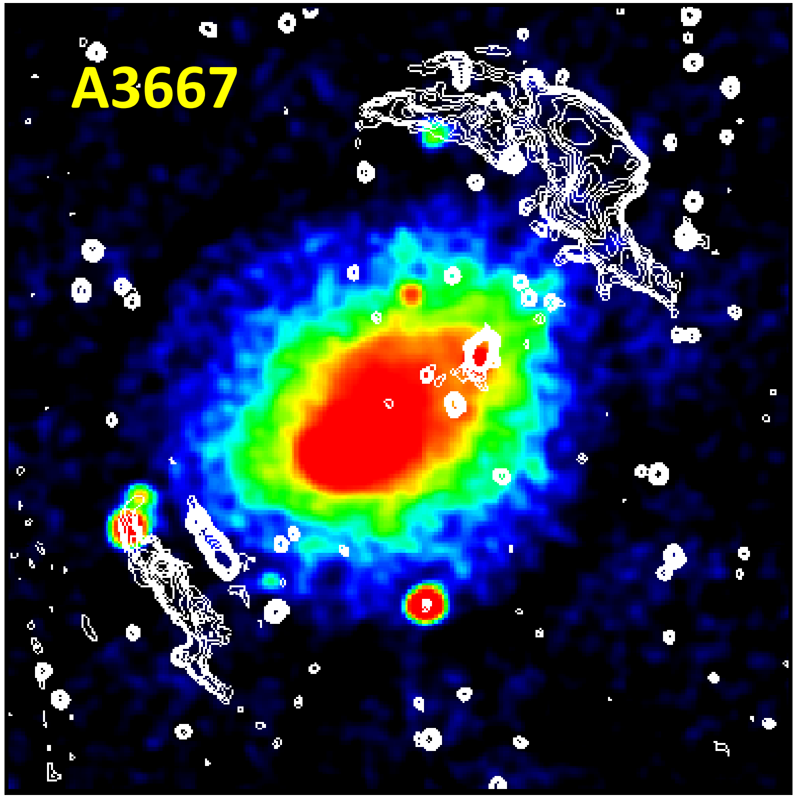


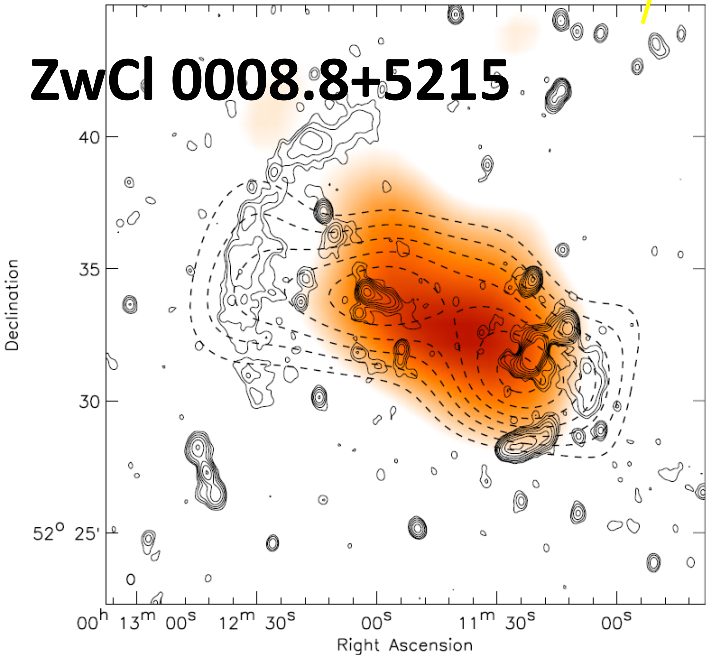
Outline

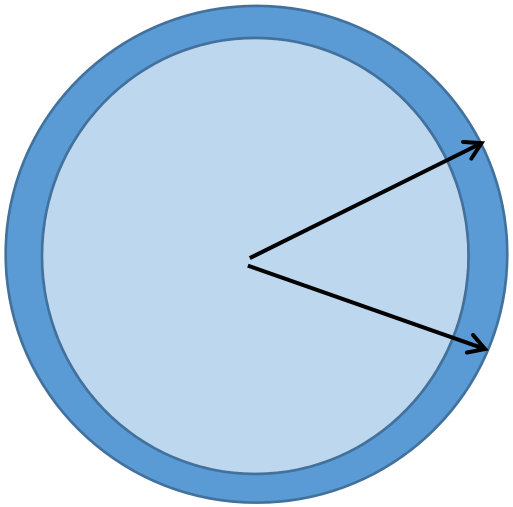
1. **Radio Synchrotron Emission From Weak Decelerating Spherical Shocks**
2. **Injection of suprathermal particles into DSA**

Radio Relic Shocks







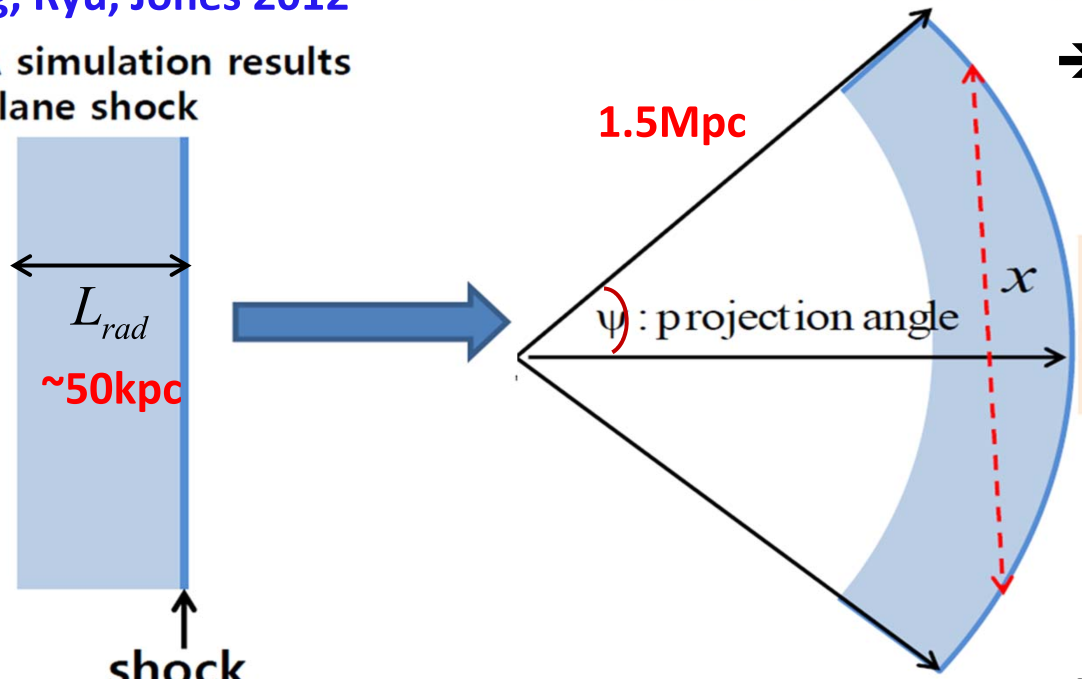


Radio Relics:
Some portions of thin spherical shells filled with relativistic electrons projected onto the sky with different viewing angles.

Kang, Ryu, Jones 2012

DSA simulation results at plane shock

mapping onto a spherical shell



➔ **Projection onto the sky plane**

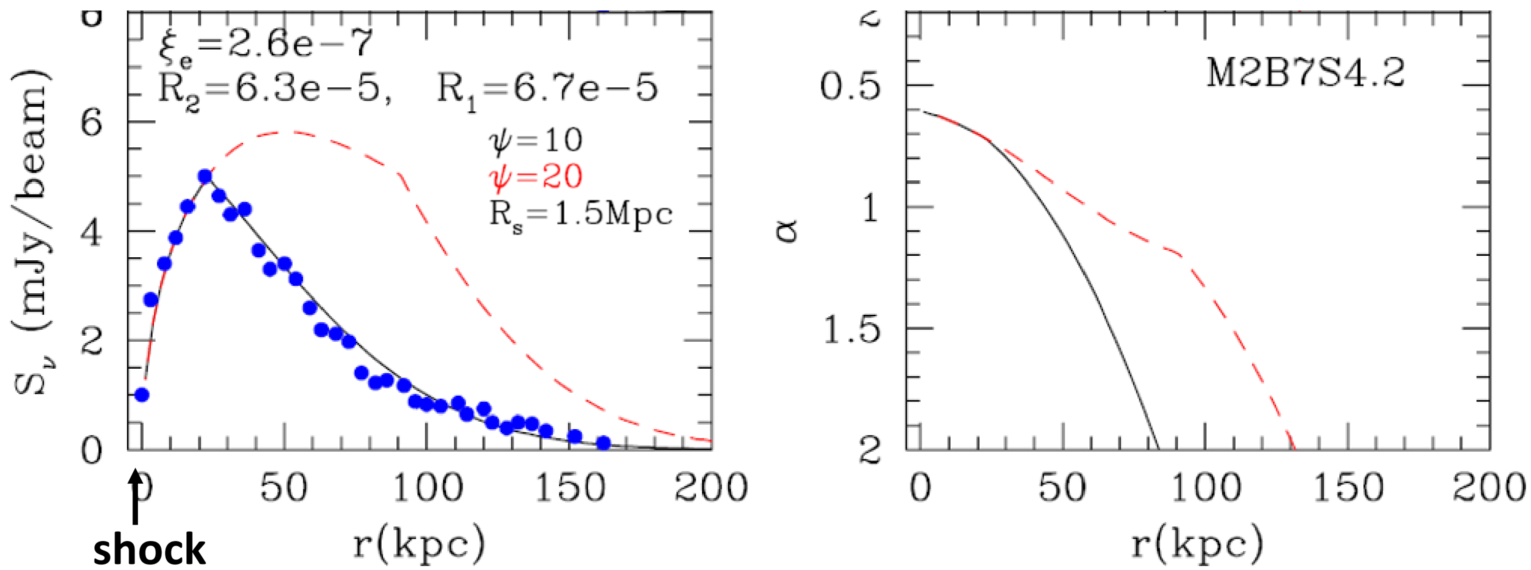
Synchrotron emissivity

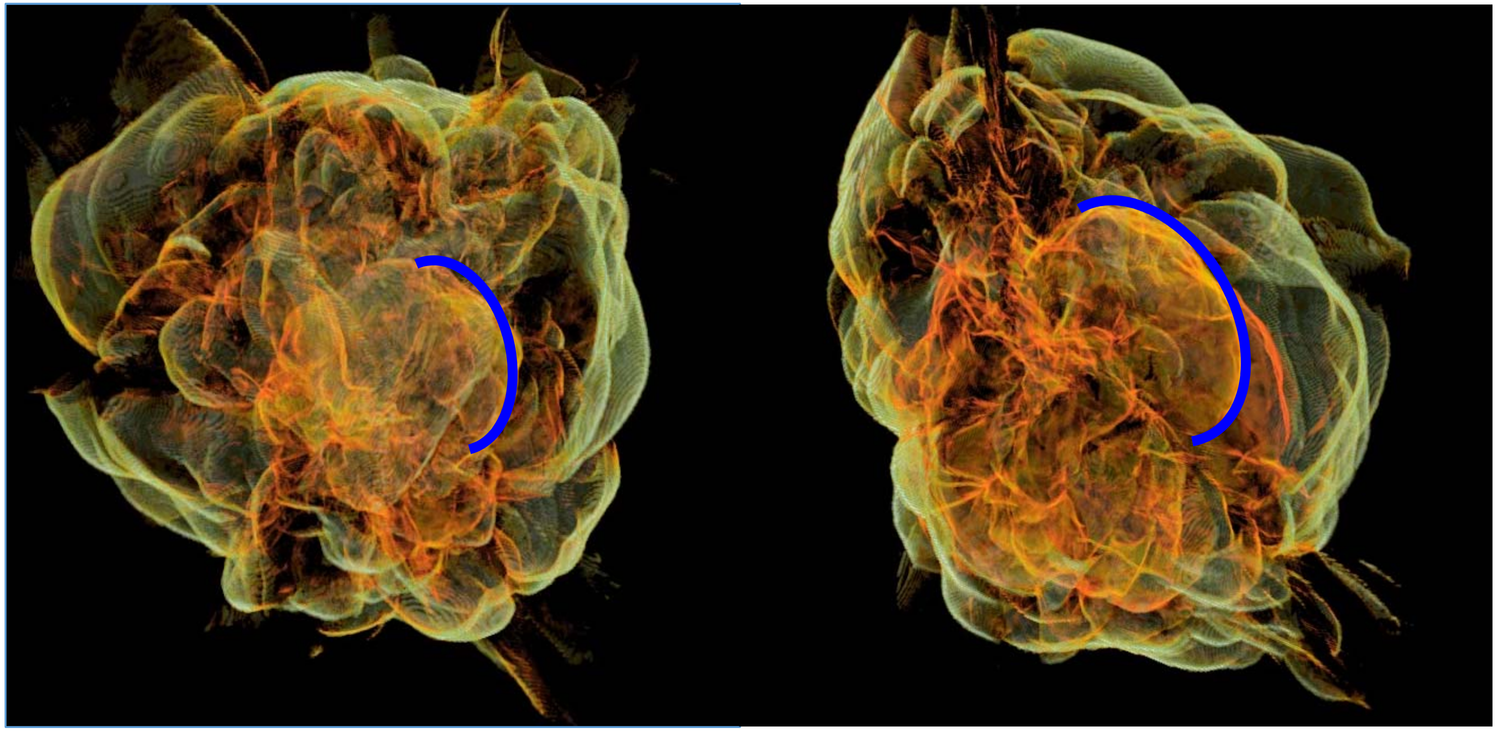
$$I_\nu = \int j_\nu(x)dx$$

integration along lines of sight

shock

Thin shell approximation is valid.





Spherically expanding shocks : How about time-dependence ?

deceleratng ? accelerating ? coasting with constant speed ?

Examine the time-dependence with a heuristic model of Sedov Blast Wave.

$$R_s(t) = r_o(t/t_o)^{2/5}, \quad u_s(t) = u_o(t/t_o)^{-3/5}, \; M_s(t) = 4.5\cdot(t/t_o)^{-3/5}$$

$$r_o = 1.0\mathrm{Mpc}, \qquad u_o = 3\times10^3\,\mathrm{km/s}$$

$$t_o = 1.3\times10^8\,\mathrm{yr} \sim 3.4\cdot t_{rad}$$

$$t_{rad}(\gamma_e) = 3.8\times10^7\,\mathrm{yr}\,(\frac{B_e}{8\mu\mathrm{G}})^{-2}(\frac{\gamma_e}{10^4})$$

$$B_{rad} = 3.24(1+z)^2\,\mu\mathrm{G}, \quad z = 0.2$$

DSA simulations of Spherical Shocks in test-particle limit

in a co-expanding frame which expands with the spherical shock.

ordinary gasdynamics EQs

$$\frac{\partial\tilde{\rho}}{\partial t}+\frac{1}{a}\frac{\partial(\upsilon\tilde{\rho})}{\partial x}=-\frac{2}{ax}\tilde{\rho}\upsilon$$

$$\frac{\partial(\tilde{\rho}\upsilon)}{\partial t}+\frac{1}{a}\frac{\partial(\tilde{\rho}\upsilon^2+\tilde{P}_g)}{\partial x}=-\frac{2}{ax}\tilde{\rho}\upsilon^2-\frac{\dot{a}}{a}\tilde{\rho}\upsilon-\ddot{a}x\tilde{\rho}$$

$$\frac{\partial(\tilde{\rho}\tilde{e}_g)}{\partial t}+\frac{1}{a}\frac{\partial(\tilde{\rho}\tilde{e}_g\upsilon+\tilde{P}_g\upsilon)}{\partial x}=-\frac{2}{ax}(\tilde{\rho}\tilde{e}_g\upsilon+\tilde{P}_g\upsilon)-2\frac{\dot{a}}{a}\tilde{\rho}\tilde{e}_g-\ddot{a}x\tilde{\rho}\upsilon-\tilde{L}(x,t)$$

Diffusion Convection Eq. for $g_e=f_e(r,p,t)p^4$ **Electrons only**

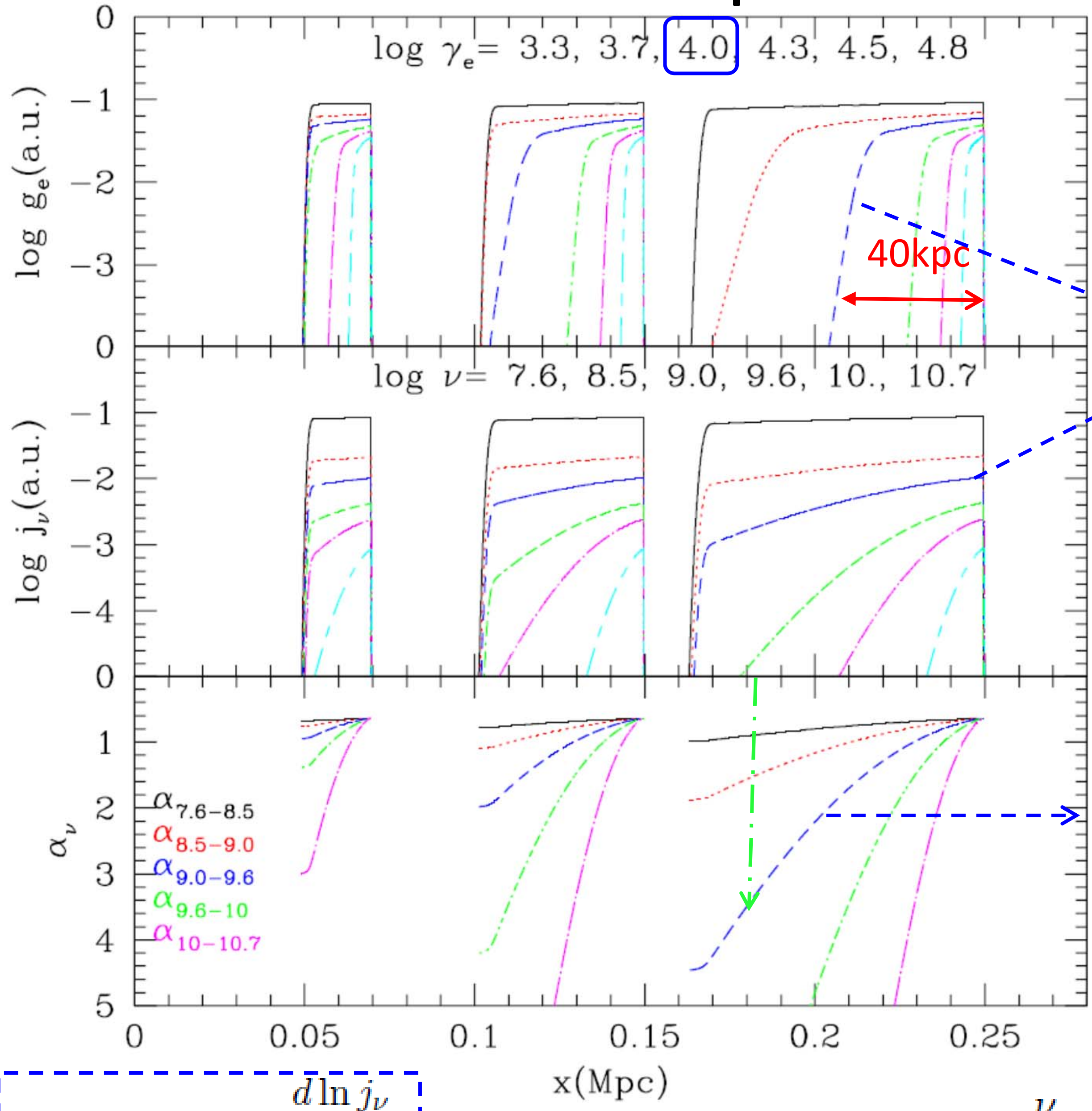
$$\frac{\partial\tilde{g}_e}{\partial t}+\frac{\upsilon}{a}\frac{\partial\tilde{g}_e}{\partial x}=[\frac{1}{3ax}\frac{\partial}{\partial x}(x^2\upsilon)+\frac{\dot{a}}{a}](\frac{\partial\tilde{g}_e}{\partial y}-4\tilde{g}_e)+3\frac{\dot{a}}{a}\tilde{g}_e+\frac{1}{a^2x^2}\frac{\partial}{\partial x}(x^2\kappa\frac{\partial\tilde{g}_e}{\partial x})+p\frac{\partial}{\partial y}(\frac{b}{p^2}\tilde{g}_e)$$

$\tilde{g}=g\cdot a^3$, $x=r/a$: co-moving coordinate, $a=$ expansion factor, $y=\ln p$,

No P_{cr} feeback due to CR protons: test-particle limit

CRASH code in 1D spherical geometry: Kang & Jones 2006

Plane shock with a constant speed



$u_s = 3.5\times10^3\,\mathrm{km/s}$

$M_s = 4.5,$

$t_{age} = (1.8,\ 4.4,\ 8.0)\times10^7\,\mathrm{yr}$

$B_1 = 2\mu\mathrm{G},\ B_2 = 7\mu\mathrm{G}$

$\gamma_e = 10^4$

$\nu_{peak} = 1\,\mathrm{GHz}$

$L(j_{1\mathrm{GHz}}) > L(\gamma_e = 10^4)$

much broader due to contribution from lower energy electrons

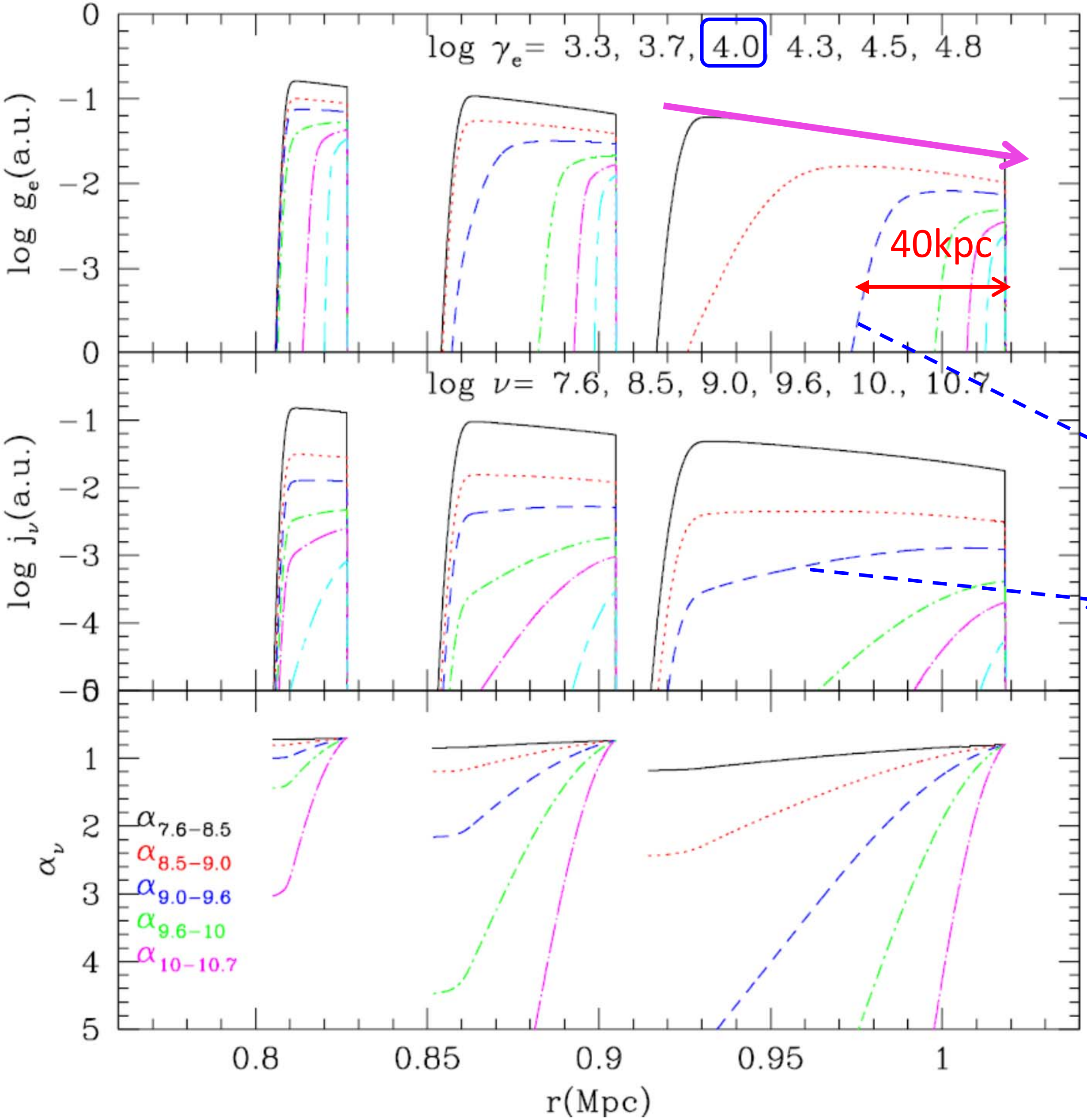
$\alpha_{1-4\mathrm{GHz}}$

shape of $j_{4\mathrm{GHz}}$

$$\alpha_{\log\nu_1-\log\nu_2} = -\frac{d\ln j_\nu}{d\ln\nu}$$

$$\nu_{\rm peak} \approx 0.63\mathrm{GHz}\left(\frac{\gamma_e}{10^4}\right)^2\left(\frac{B}{5\,\mu\mathrm{G}}\right)$$

decelerating spherical shock



$$R_s(t) \sim r_o (t/t_o)^{2/5}$$

$$u_s(t) \sim u_o (t/t_o)^{-3/5}$$

$$r_o = 1.0\,\mathrm{Mpc}$$

$$u_o = 2.3\times10^3\,\mathrm{km/s}$$

$$t_o = 1.7\times10^8\,\mathrm{yr}$$

$$t_{age} = (1.7,\ 4.3,\ 8.8)\times10^7\,\mathrm{yr}$$

$$\gamma_e = 10^4$$

$$\nu_{peak} = 1\,\mathrm{GHz}$$

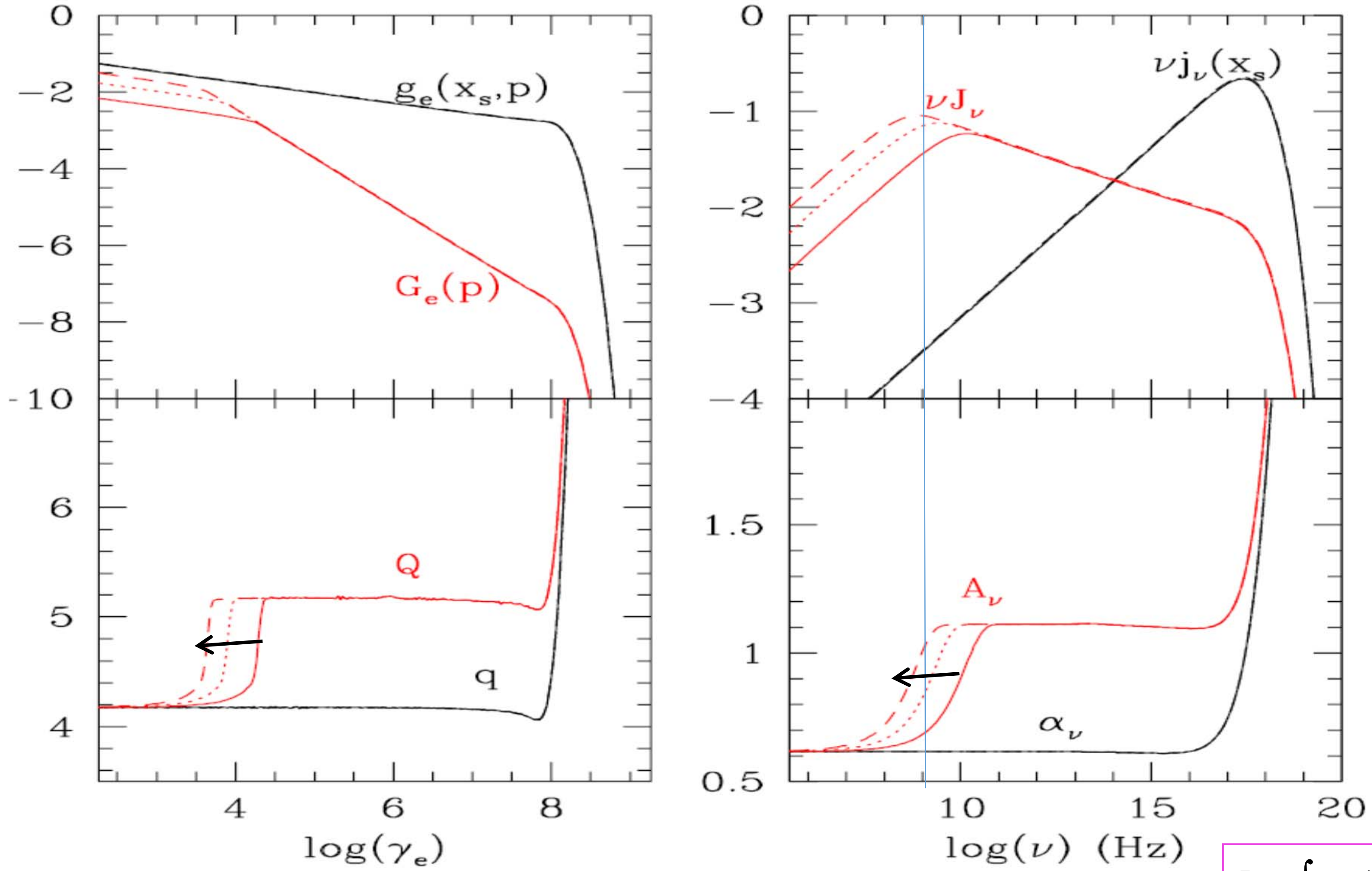
$$L(j_{1\mathrm{GHz}}) > L(\gamma_e = 10^4)$$

-declining electron flux

-steepening of f_e (p)

$$f_{e,2}(p) \propto \left(\frac{p}{p_{inj}}\right)^{-q}, \quad q = \frac{3r}{r-1}$$

Plane shock with a constant speed: at the shock vs. volume integrated



$$G_e(p) = \int f_e(p,x)p^4 dx$$

$$Q = -\frac{\partial \ln G_e}{\partial \ln p} + 4$$

$$Q \approx q + 1$$

$$u_s = 3.5\times10^3 \text{km/s}$$

$$M_s = 4.5,$$

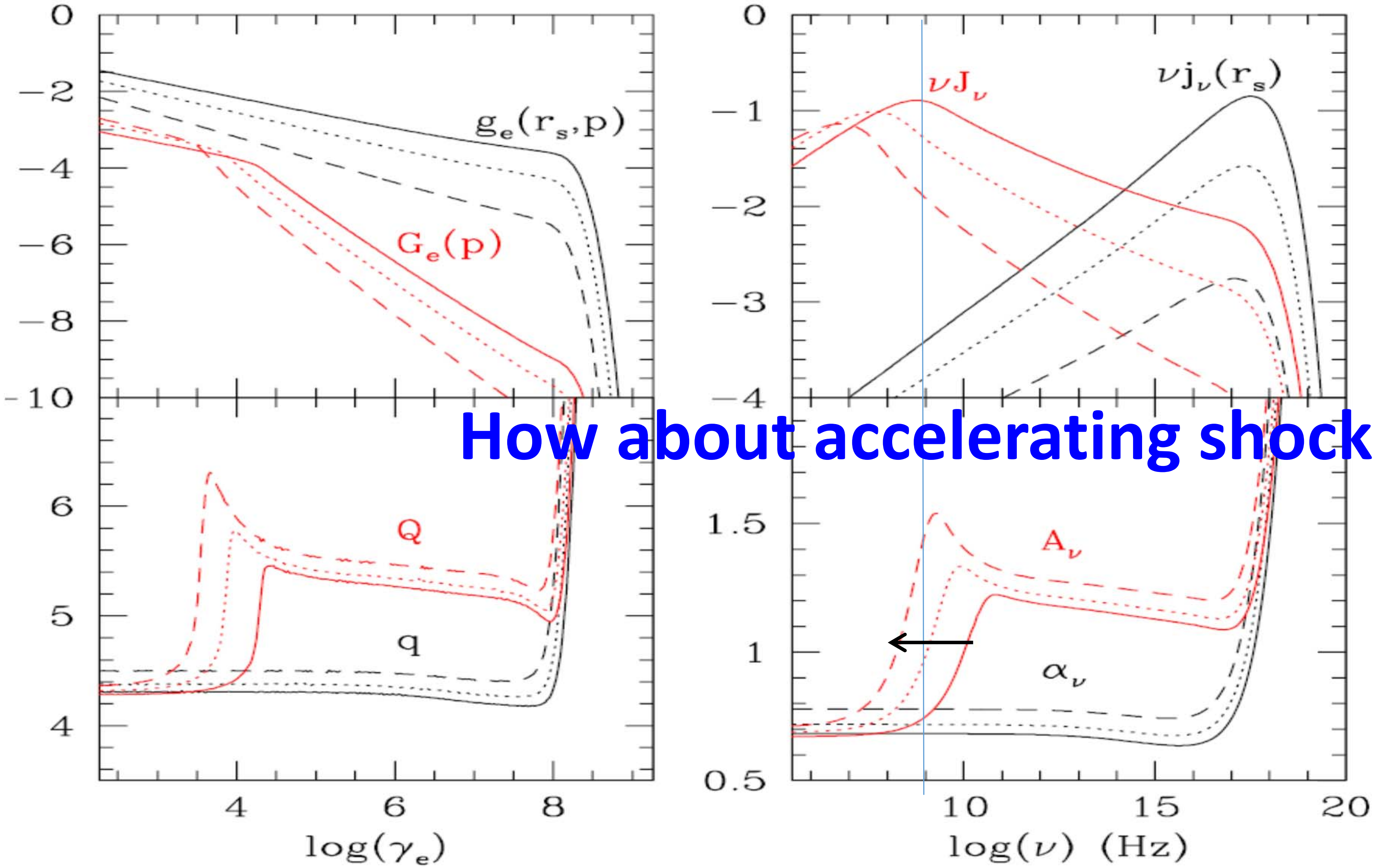
$$t_{age} = (1.8,\ 4.4,\ 8.0)\times10^7 \text{yr}$$

$$J_\nu = \int j_\nu(x)dx$$

$$A_\nu = -\frac{\partial \ln J_\nu}{\partial \ln \gamma}$$

$$A_\nu \approx \alpha_\nu + 0.5$$

decelerating spherical shock: at the shock vs. volume integrated



How about accelerating shock ?

$$G_e(p) = \int f_e(p,r)\, p^4 \cdot 4\pi r^2 dr$$

$$Q = -\frac{\partial \ln G_e}{\partial \ln p} + 4$$

$$Q \neq q + 1$$

$$u_s(t) \sim 2.3\times10^3\,\mathrm{km/s}\,(t/t_o)^{-3/5}$$

$$t_o = 1.7\times10^8\,\mathrm{yr}$$

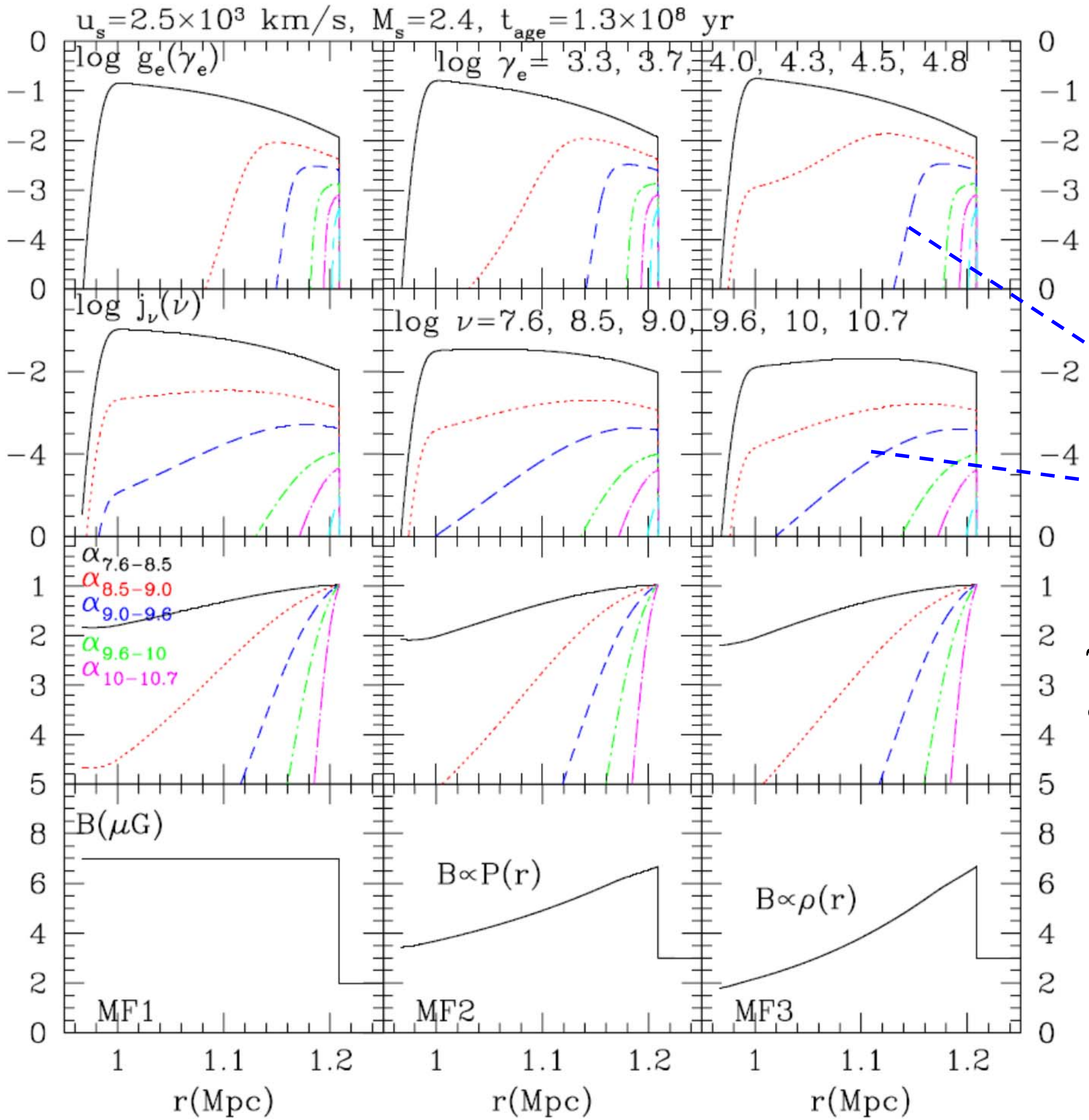
$$t_{age} = (1.7,\ 4.3,\ 8.8)\times10^7\,\mathrm{yr}$$

$$J_\nu = \int j_\nu(r)\cdot 4\pi r^2 dr$$

$$A_\nu = -\frac{\partial \ln J_\nu}{\partial \ln \gamma}$$

$$A_\nu \neq \alpha_\nu + 0.5$$

Spherical shock with different B(r<r_s)



Because iC scattering of CMBR provides the base-line cooling, $f_e(p,r)$ do not depend sensitively on *B*(*r*).

$$B_{rad} = 3.24(1+z)^2 \mu G$$

$$\gamma_e = 10^4$$

$$\nu_{peak} = 1\,\mathrm{GHz}$$

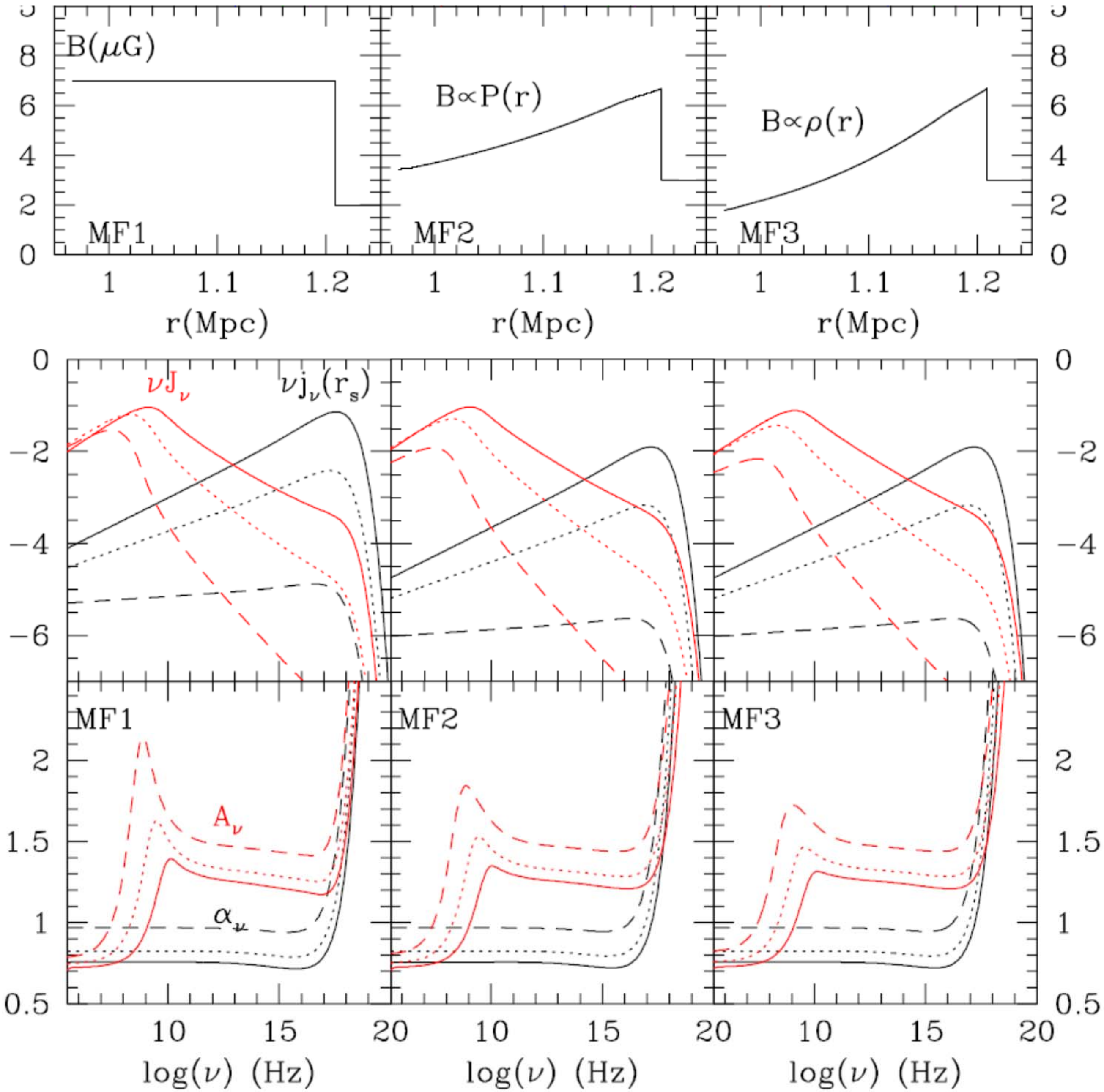
Electrons in a broad range of γ_e contribute emission to j_ν at a given frequency.

➔ Similar profiles of $j_\nu(r)$

Heuristic Models:

B(r) decreases behind the shock with L~100-150kpc.

Spherical shock with different B(r<r_s)



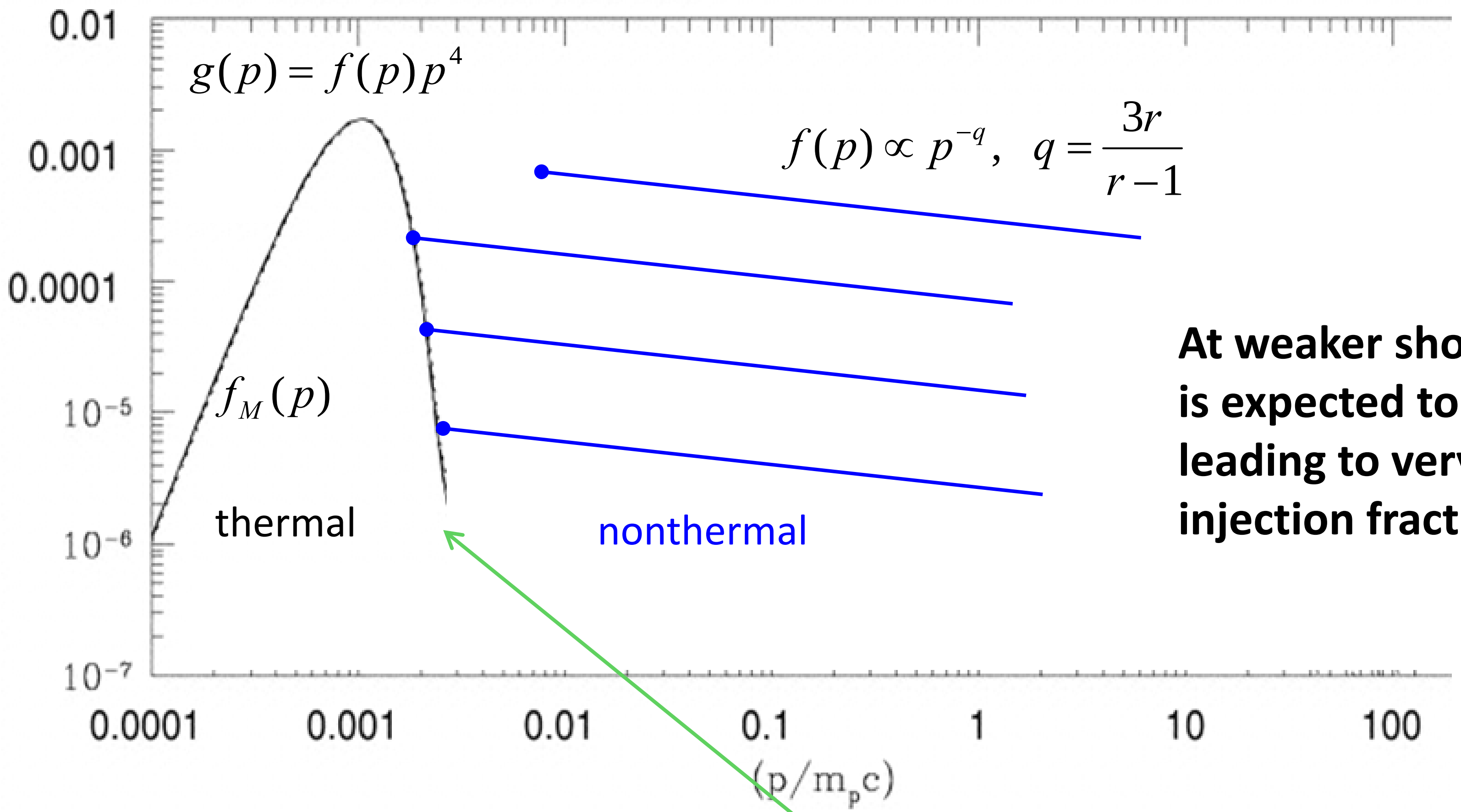
Heuristic Models:
B(r) decreases behind the shock with L~100-150kpc.

Nonlinear curvatures in the volume integrated J_ν and A_ν become less distinct in the case of decaying B(r).

Summary for the comparison of plane vs. spherical shocks

1. **The electron energy spectrum at the spherical shock has reached the steady state defined by the instantaneous shock parameters.**
2. **The volume integrated, $G_e(p)$ and J_ν could depend on the time-dependent history of shock parameters.** $R_s(t),\ u_s(t),\ M_s(t),$
3. **In the case of evolving shocks, one needs to be cautious about interpreting observed radio spectra by adopting simple DSA models in the test-particle regime.**
4. **Because iC scattering of CMBR provides the base-line cooling, the electron energy spectrum do not depend sensitively on the postshock profile of *B*(*r*), if B(r) is order of microgauss.**
5. **Impacts of different *B*(*r*) profiles on the spatial profile of j_ν (*r*) and its slope are minimal, since electrons in a broad range of γ_e contribute emission to j_ν at a given frequency.**

suprathermal particles → injection into DSA: Kang et al. 2002



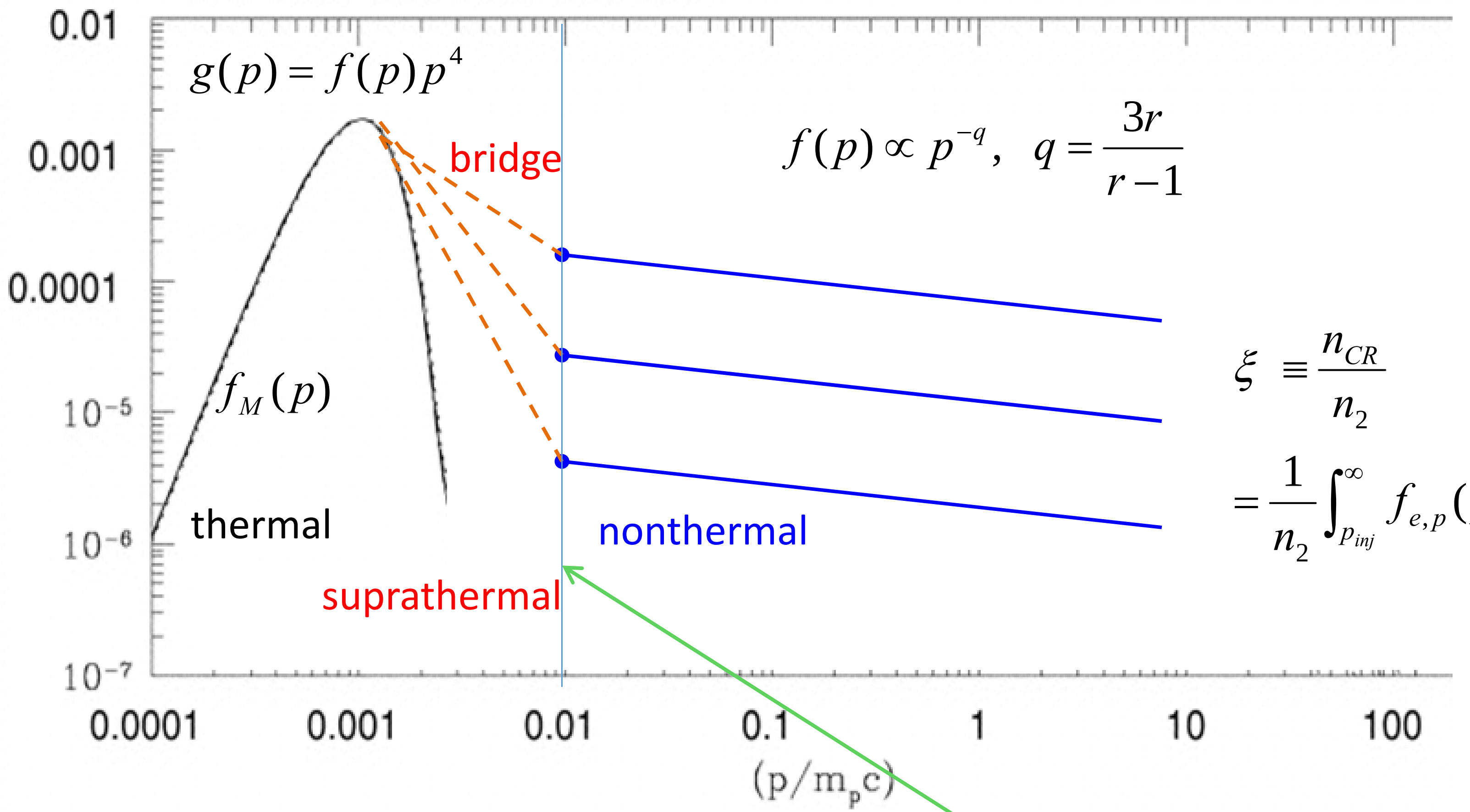
At weaker shocks, p_inj is expected to be higher, leading to very low injection fraction.

How to connect the DSA power-law to the thermal $f_M(p)$ **?**

Boundary between thermal particles and CRs ?

$$p_{inj} \sim 3-5\sqrt{2 m_p k_B T_2}$$

suprathermal particles ➔ injection into DSA: new picture



$$\xi \equiv \frac{n_{CR}}{n_2} = \frac{1}{n_2}\int_{p_{inj}}^{\infty} f_{e,p}(p)\cdot 4\pi p^2 dp$$

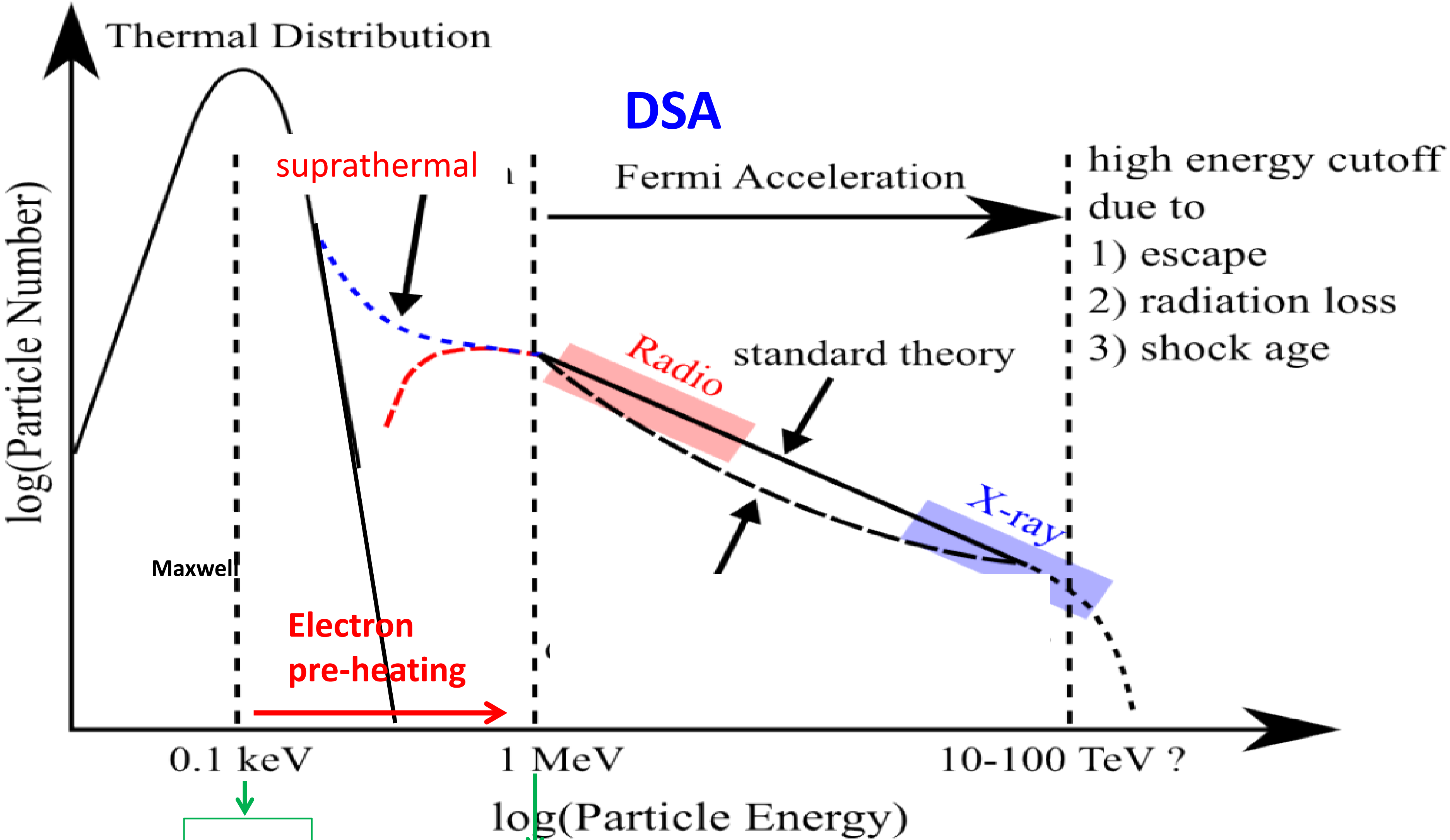
Connect the DSA power-law to the suprathermal (kappa-like) distribution?

Boundary between suprathermal particles and CRs ?

$$p_{inj} \sim 3-5\sqrt{2m_p k_B T_2}$$

Introduction of kappa-like suprathermal distirubiton → enhanced injection

Electron pre-heating : instabilities, wave-particle interaction

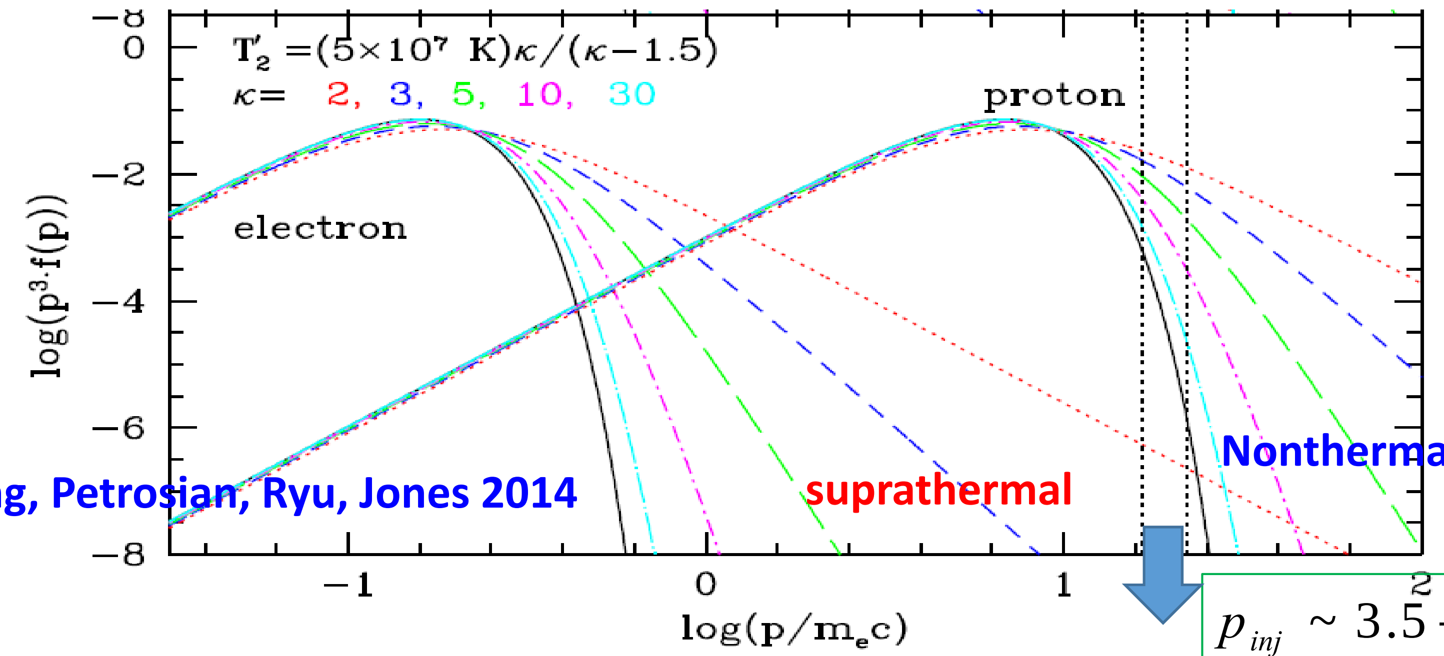


$p_{th,e}$

$$p_{inj} \sim 3\sqrt{2 m_p k_B T_2} \sim 130\ p_{th,e}$$

from Amano 2009

Kappa-distribution of suprathermal particles ➔ injection into DSA



$$p_{inj} \sim 3.5 - 4\sqrt{2 m_p k_B T_2}$$
$$\sim 150 - 170 \; p_{th,e}$$

$$f_\kappa(p) = \frac{n_2}{\pi^{1.5}} \, p_{\rm th}^{-3} \frac{\Gamma(\kappa+1)}{(\kappa-3/2)^{3/2}\Gamma(\kappa-1/2)} \cdot \left[1 + \frac{p^2}{(\kappa-3/2)p_{\rm th}^2}\right]^{-(\kappa+1)}$$

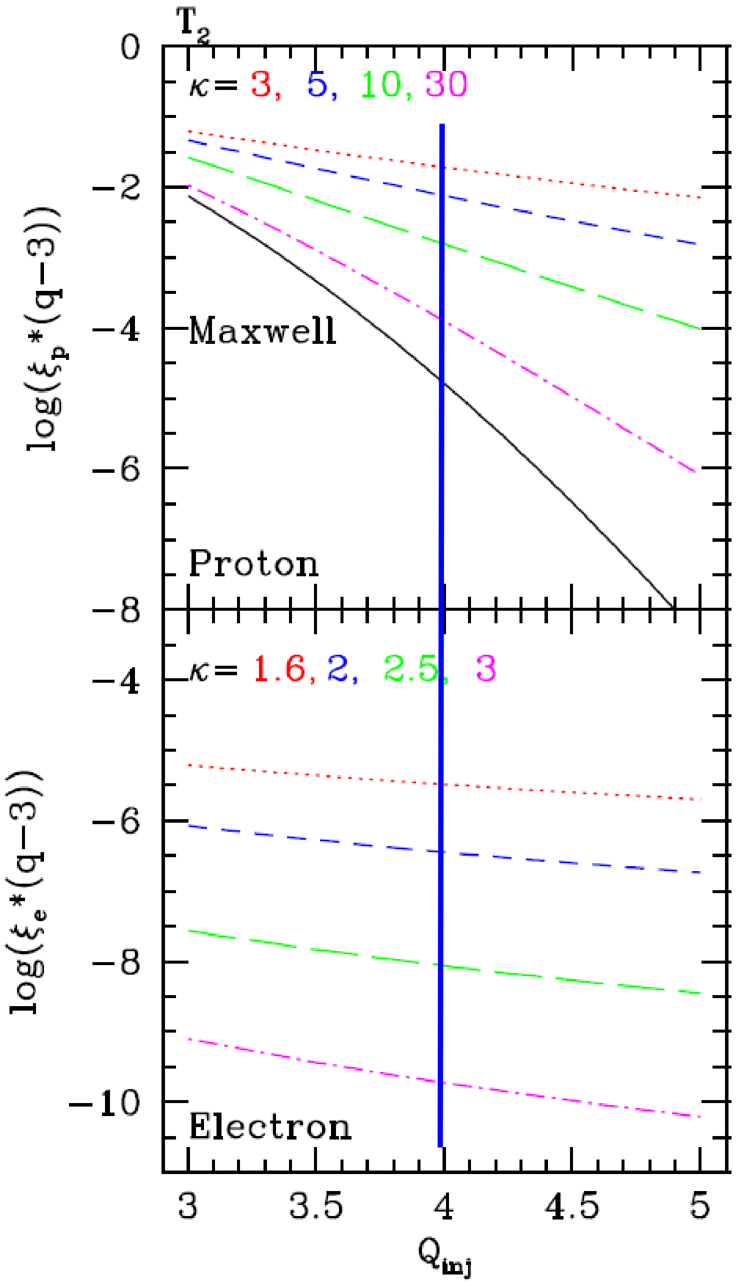
$$\xi_{e,p} = \frac{1}{n_2}\int_{p_{inj}}^{\infty} f_{e,p}(p)\cdot 4\pi p^2 dp$$ **Injection efficiency is affected by p_inj.**

Development of suprathermal particles up to $\gamma_e > 20$

Pre-heating via wave-particle interactions ?

or Fermi-like acceleration via reflection & scattering between the shock and foreshock waves ?

Injection fraction by number



$$\xi_{e,p} \equiv \frac{n_{CR}}{n_2} = \frac{1}{n_2}\int_{p_{inj}}^{\infty} f_{e,p}(p)\cdot 4\pi p^2 dp$$

depends on $p_{inj} = Q_{inj}(M_s)\cdot p_{th,p}$

For kappa-distribution, $\xi_\kappa >> \xi_{\text{Maxwell}}$

$$\xi_\kappa = \frac{4}{\sqrt{\pi}}\frac{Q_{\text{inj}}^3}{(q-3)}\frac{\Gamma(\kappa+1)}{(\kappa-3/2)^{3/2}\Gamma(\kappa-1/2)} \times \left[1+\frac{Q_{\text{inj}}^2}{(\kappa-3/2)}\right]^{-(\kappa+1)}$$

e.g. $Q_{inj} = 4$

For $\kappa_p = 10,\ \xi_p \sim 10^{-2.7}$

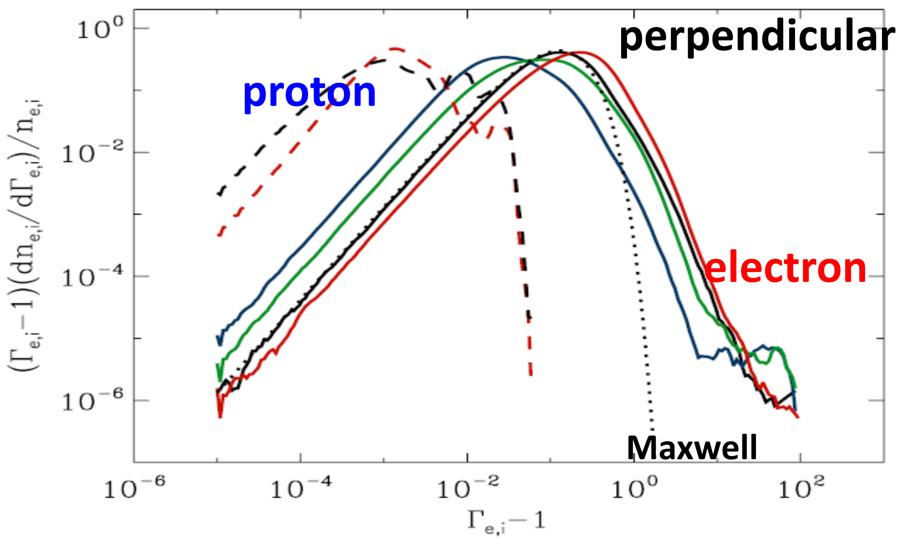
$\kappa_e = 1.6,\ \xi_e \sim 10^{-5.5}$

$\Rightarrow K_{e/p} \sim 10^{-2.8}$

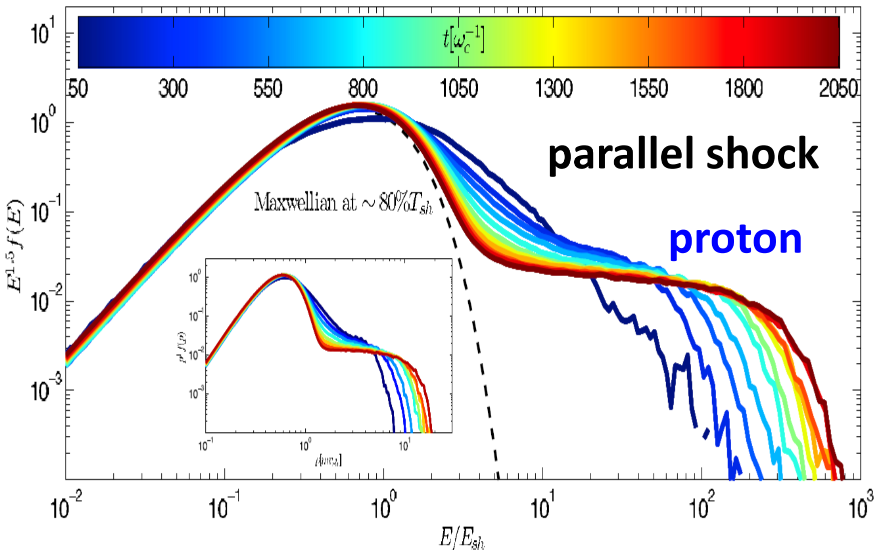
We need feedback from Plasma physics .

Kang, Petrosian, Ryu, Jones 2014

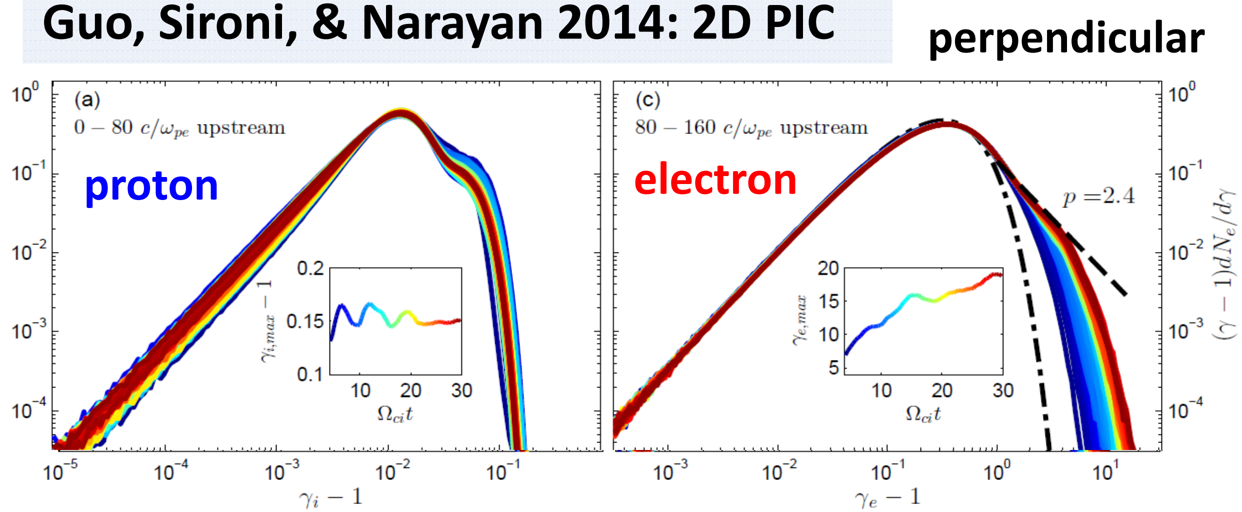
Riquelme & Spitkovsky 2011: PIC



Caprioli & Sptikovsky 2014: Hybrid simulation



Guo, Sironi, & Narayan 2014: 2D PIC

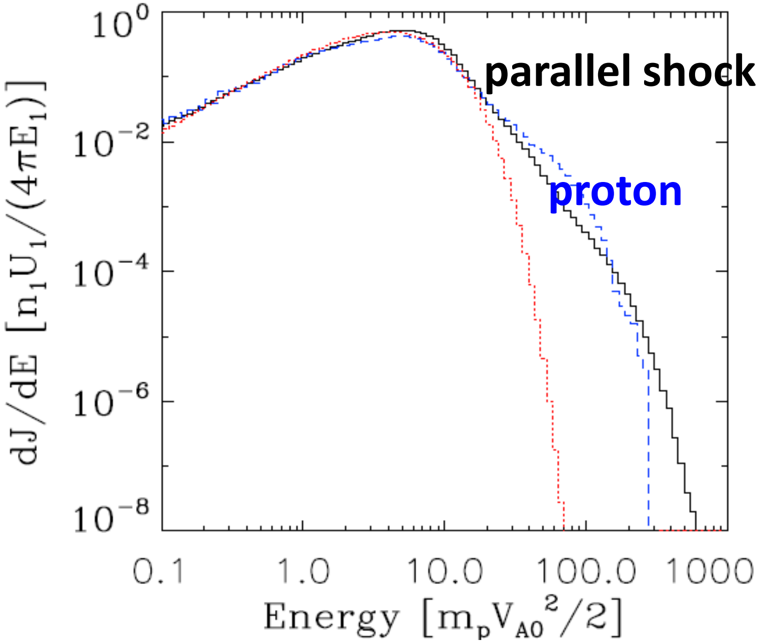


Minimal SDA for protons
→ No acceleration

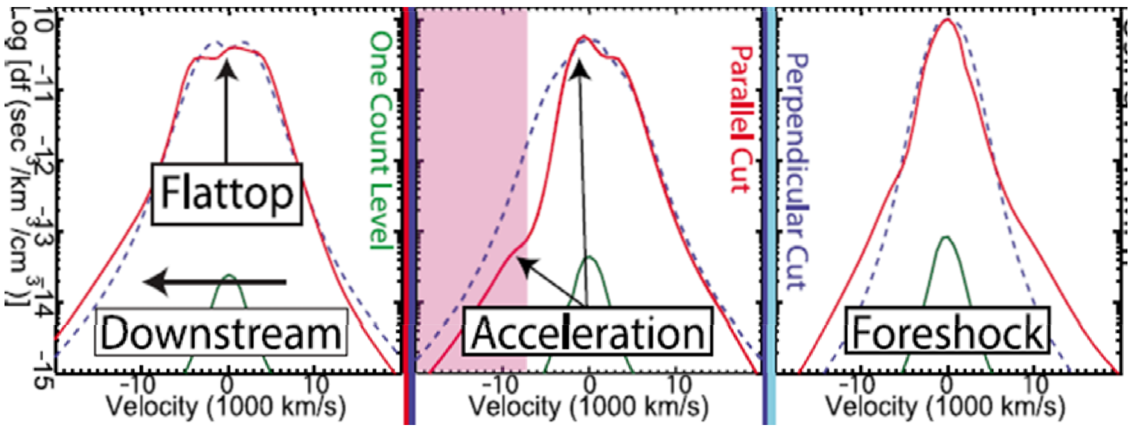
Multiple SDA for electrons
→Nonthermal tail
→Pre-acceleration for DSA

$$\theta_B = 63^\circ, \quad M_A \approx 8.2, \quad M_s = 3, \quad u_0 = 0.15c, \quad \beta_p \approx 25 \ \text{: plasma beta}$$

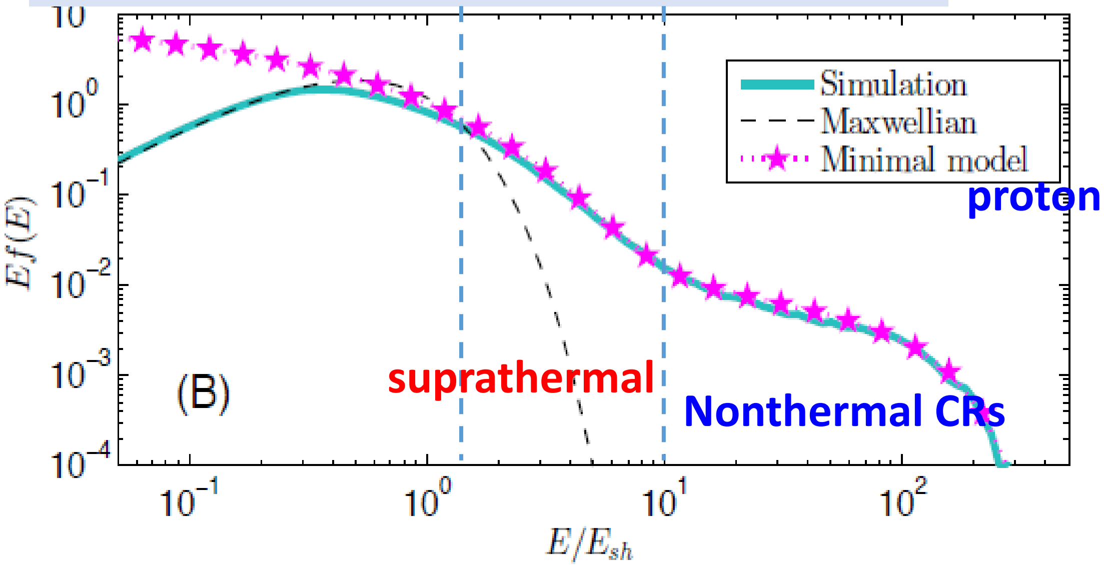
Guo & Giacalone 2013: hybrid



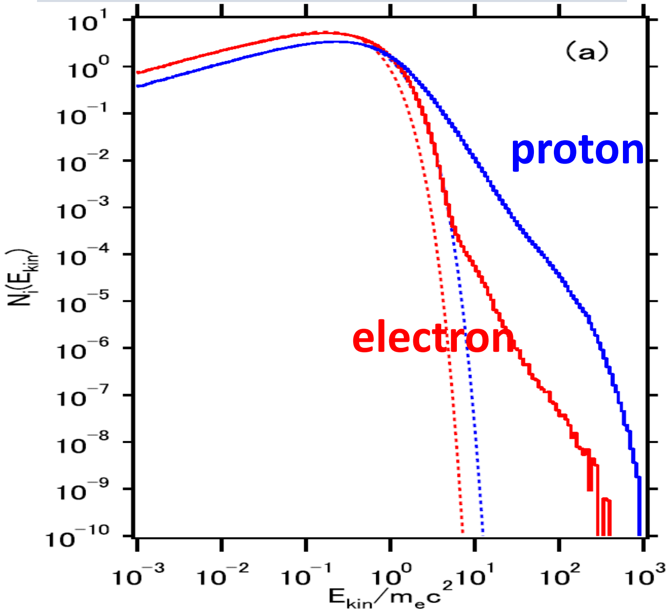
Wilson III et al. 2012: IPM shock



Caprioli & Sptikovsky 2014:Hybrid

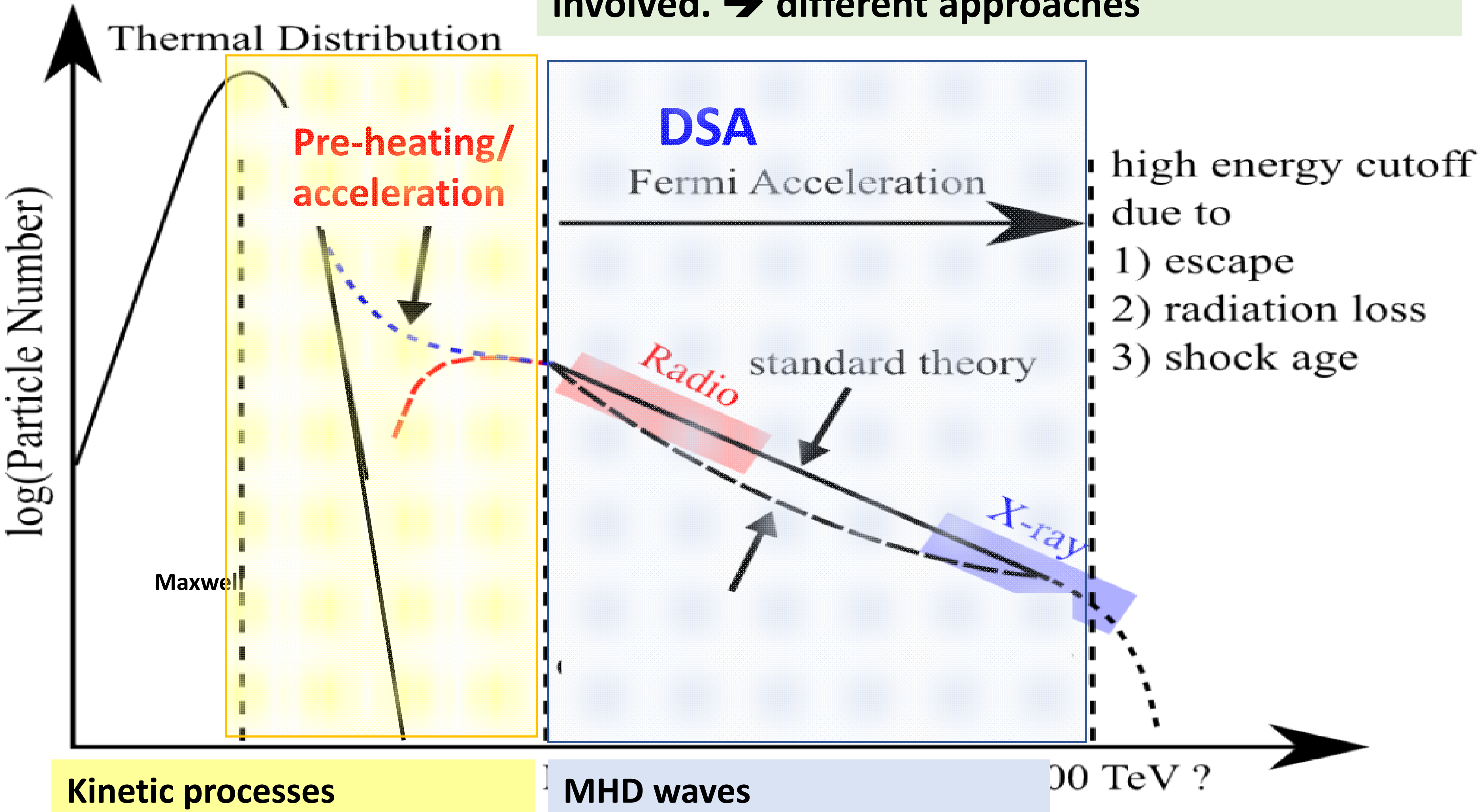


Kato 2014: 1D PIC



Electron Injection

Wide ranges of space, time, energy scales are involved. ➔ different approaches



Kinetic processes
PIC/Hybrid simulations
Space physics
Laboratory astrophysics

MHD waves
Nonlinear DSA
Astrophysics